Solid-State Lighting 101

2012 DOE Solid-State Lighting Market Introduction Workshop

July 17, 2012

Dr. John W. Curran,
President, LED Transformations, LLC

On behalf of the U.S. Department of Energy and NETL Morgantown

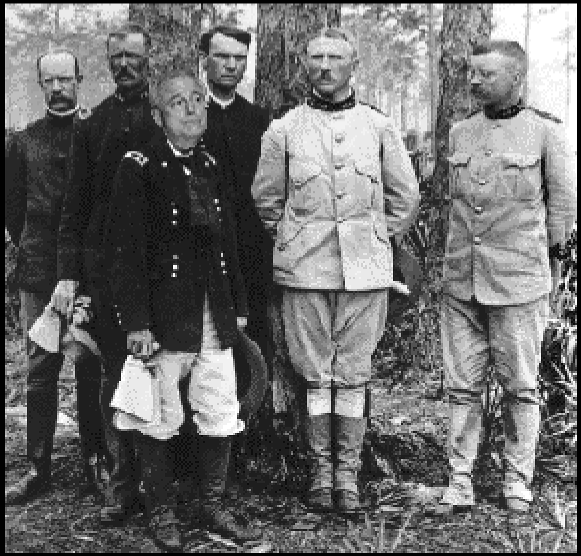
Copyright Materials

Electric Light Basics

July 17th 1912

Dr. John W. Curran,

President, LED Transformations, LLC



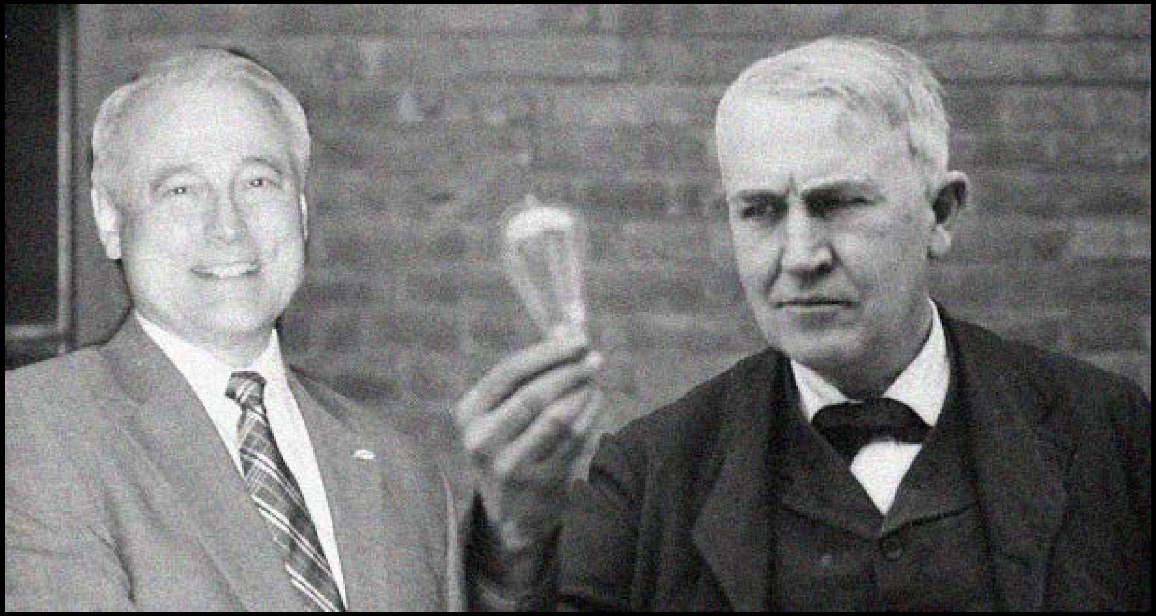
Early discussions in the Roosevelt Administration concerning the marketing issues for the electric lamp

Cost is a major issue for this new technology
Especially when average income is only $450 per year

About 0.1% of annual income

Good news – in 100 years that cost will drop to 0.001% of annual income

Edison showing off his latest model to Roosevelt's head of Electric Lighting, James Brodrick

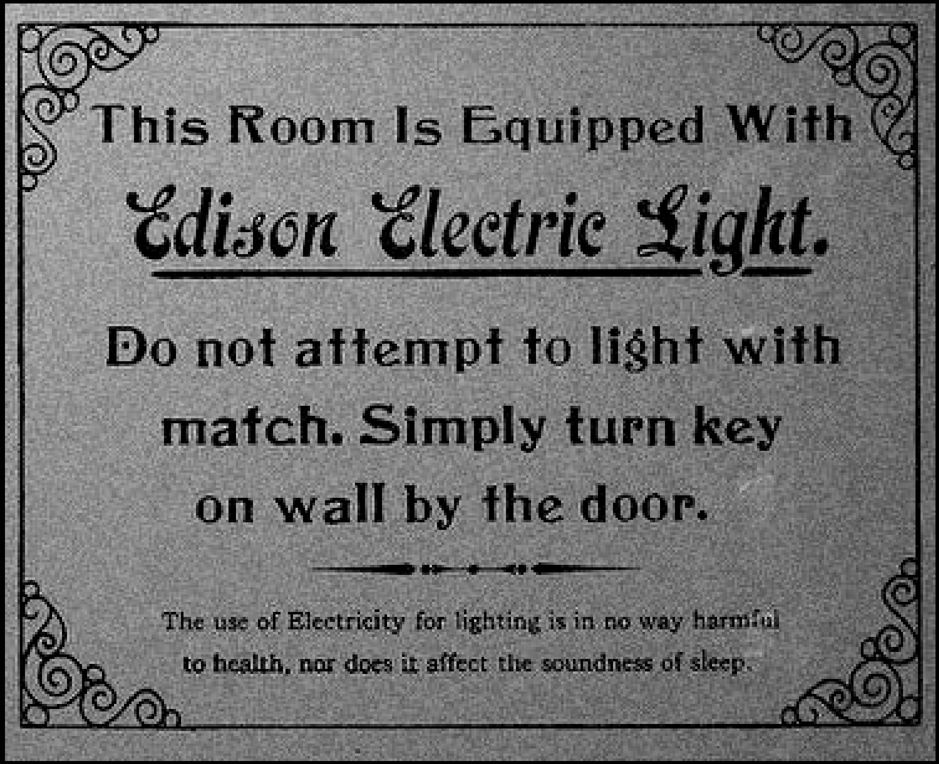


Competition spreads misinformation about the new technology

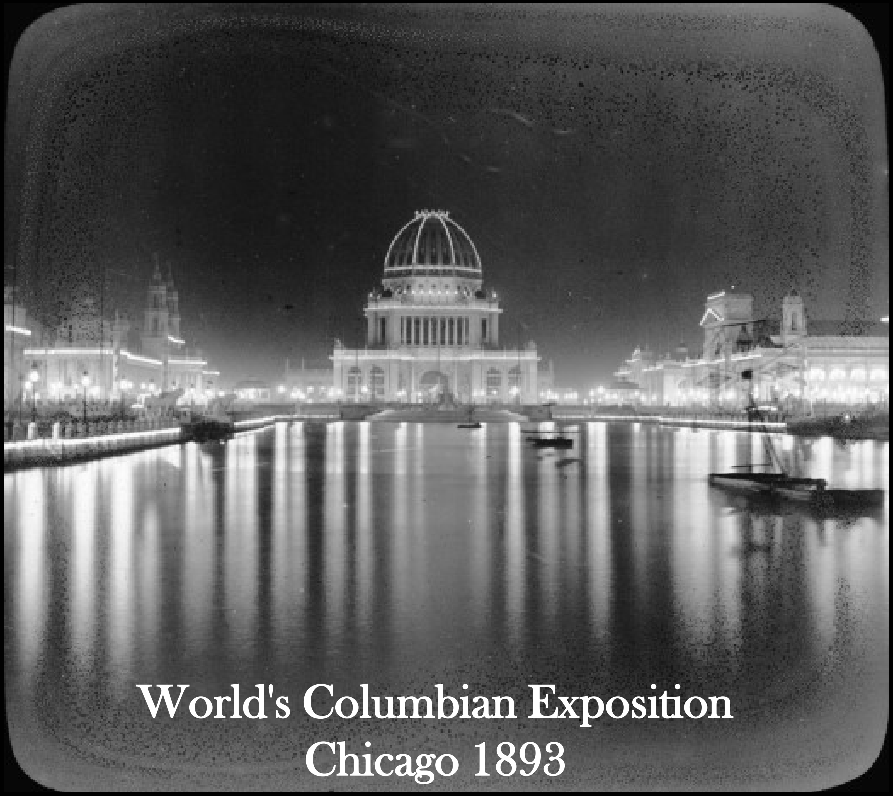
*"**Surely, my system is more important than the incandescent lamp**, which is but one of the known electric illuminating devices and admittedly not the best. Although greatly improved through chemical and metallurgical advances and skill of artisans it is still inefficient, and **the glaring filament emits hurtful rays responsible for millions of bald heads and spoiled eyes**. In my opinion, it will soon be superseded by the electrodeless vacuum tube which I brought out thirty-eight years ago, a lamp much more economical and yielding a light of indescribable beauty and softness."*

Nikola Tesla (1929)

And the technology responds



Early pre-Gateway demonstration of the technology



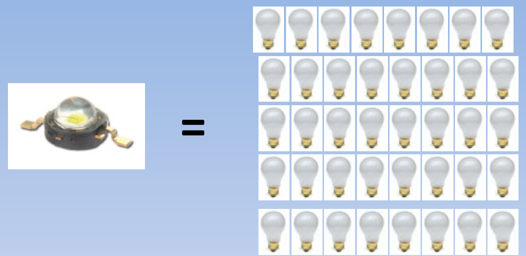
Learning Objectives

Solid-State Lighting 101

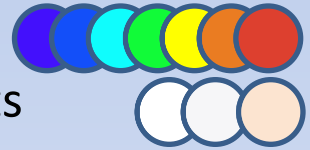
1. Understanding heat and its effect on LED luminaire performance and lifetime
2. How LEDs differ from traditional light sources in the method in which they produce light, and how those differences can affect the design of lighting projects
3. Difference between LEDs and OLEDs

Why Should I Care About LEDs?

LEDs are like no other conventional lighting source



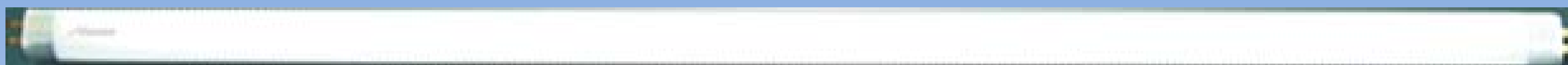
- \+ Potentially longest[1] life of any lighting sources
- \+ Very high energy efficiency
- \+ Small size and instant on allows new applications
- \+ Produces color light directly without filtering
- \+ Integrates will with other semiconductor electronic elements
- \- Thermal management requirements
- \- Cost
- \- New technology brings unfamiliar issues to architects, lighting designers, building owners and facilities managers



[1]Note: Some manufacturers have introduced products claiming long lifetimes: fluorescent tubes (55,000 hours); induction (100,000 hours)

Introduction

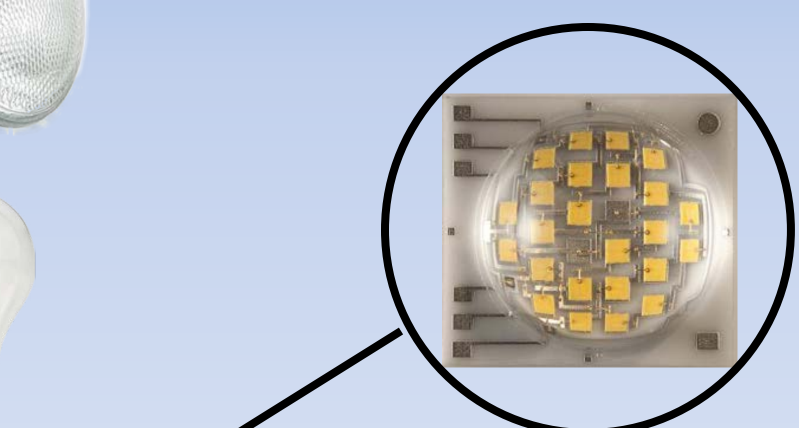
Small Size



T5 Fluorescent
1350 lumens

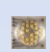
75W PAR 38 Halogen
1100 lumens

75W Incandescent
1200 lumens



Source: Cree

Cree MP-L LED
1200 lumens



Introduction

New Names & Shapes in Lighting

Traditional Lamp Suppliers

- Sylvania

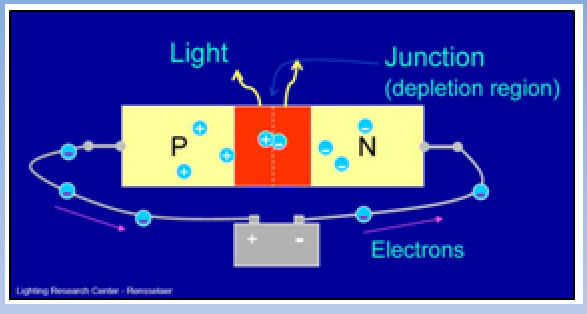
- Philips

- GE

LED Suppliers

- Osram
- Lumileds
- Cree
- Bridgelux
- Nichia
- Seoul Semiconductor
- Toshiba
- Sharp
- Toyota Gosei
- Edison Opto
- and many more…

What is an LED?



An LED (**L**ight **E**mitting **D**iode) consists of a chip of semiconducting material treated to create a structure called a p-n (positive-negative) junction

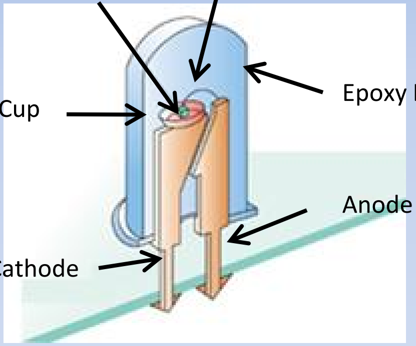


Diagram of a 5mm LED

The <u>heatsink</u> is what allows the high flux LED to generate much more light

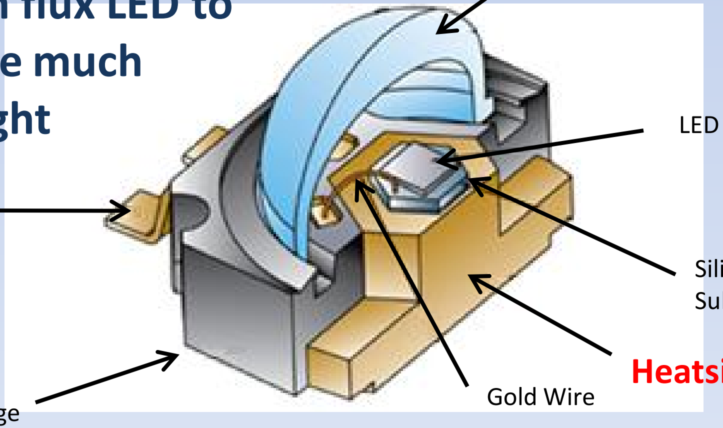
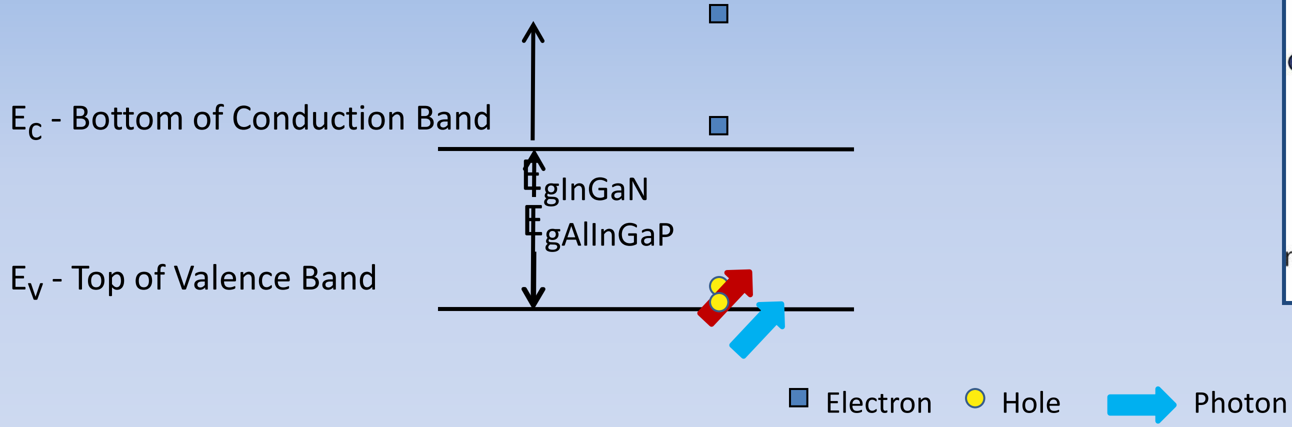
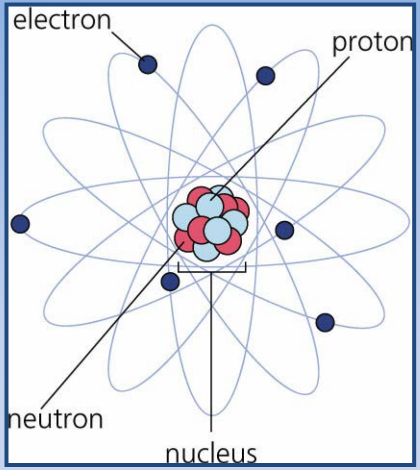


Diagram of a high flux LED

How does the LED make light?

Bandgaps – Different gaps, different colors



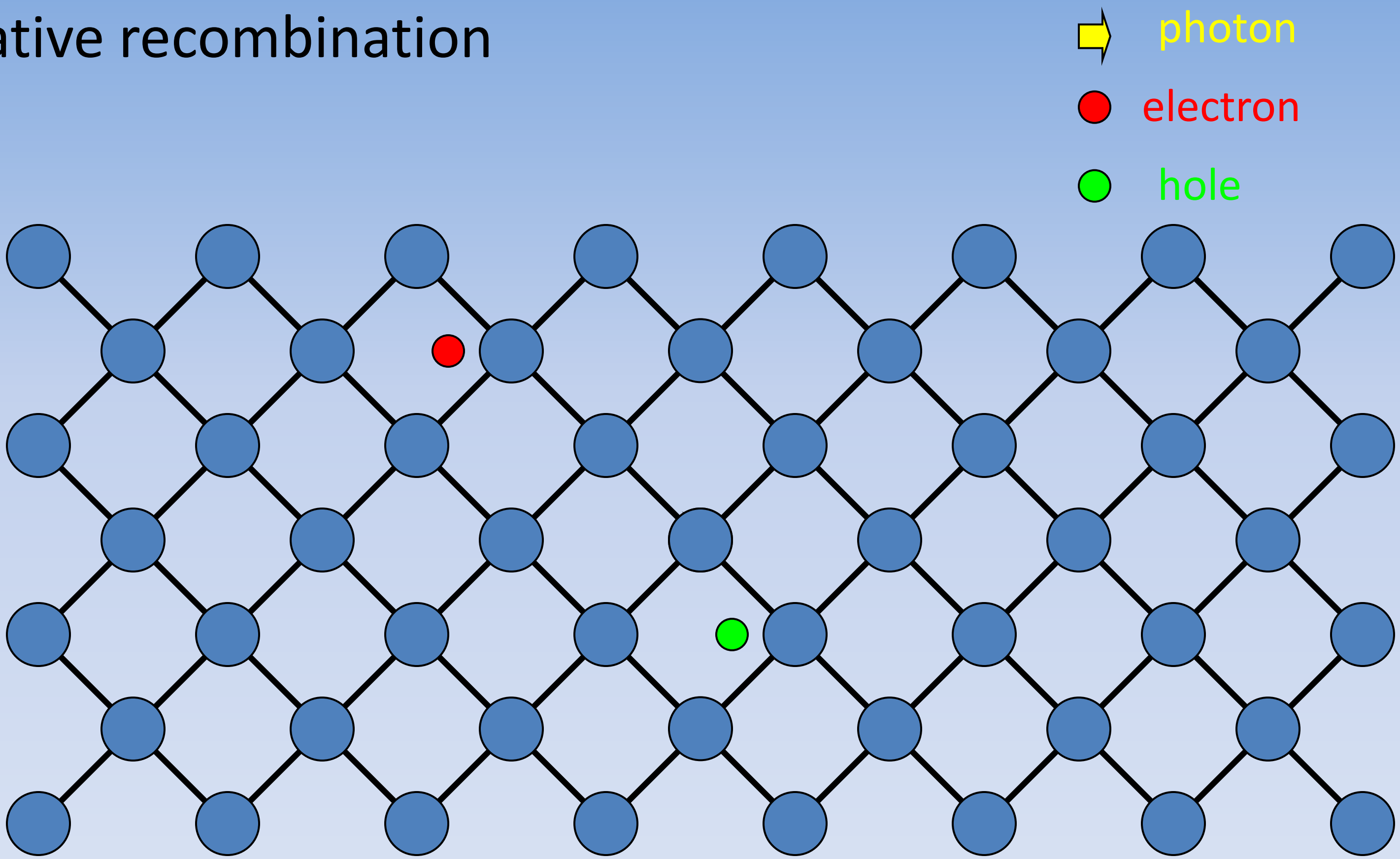


Smaller bandgap ➔ Lower energy ➔ Longer wavelength photon ➔ **Red**

Larger bandgap ➔ Higher energy ➔ Shorter wavelength photon ➔ **Blue**

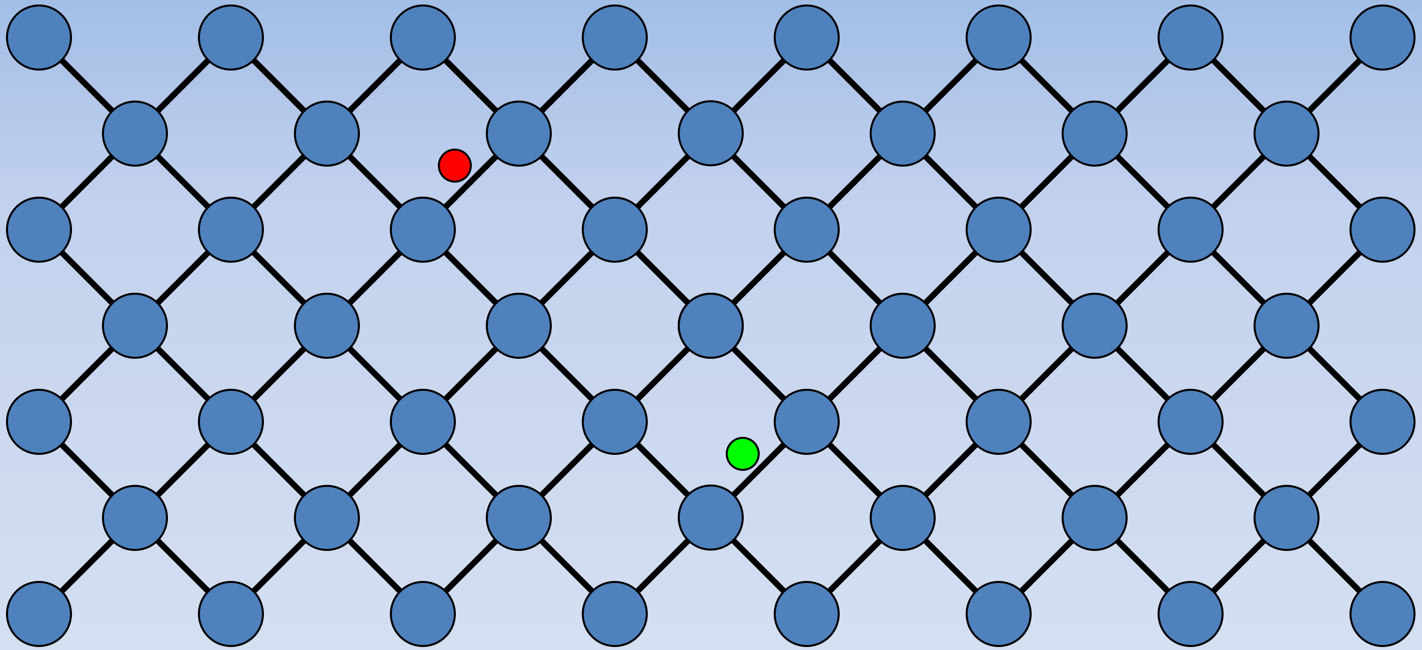
How does the LED make light?

Radiative recombination



How does the LED make light?

Non-radiative recombination

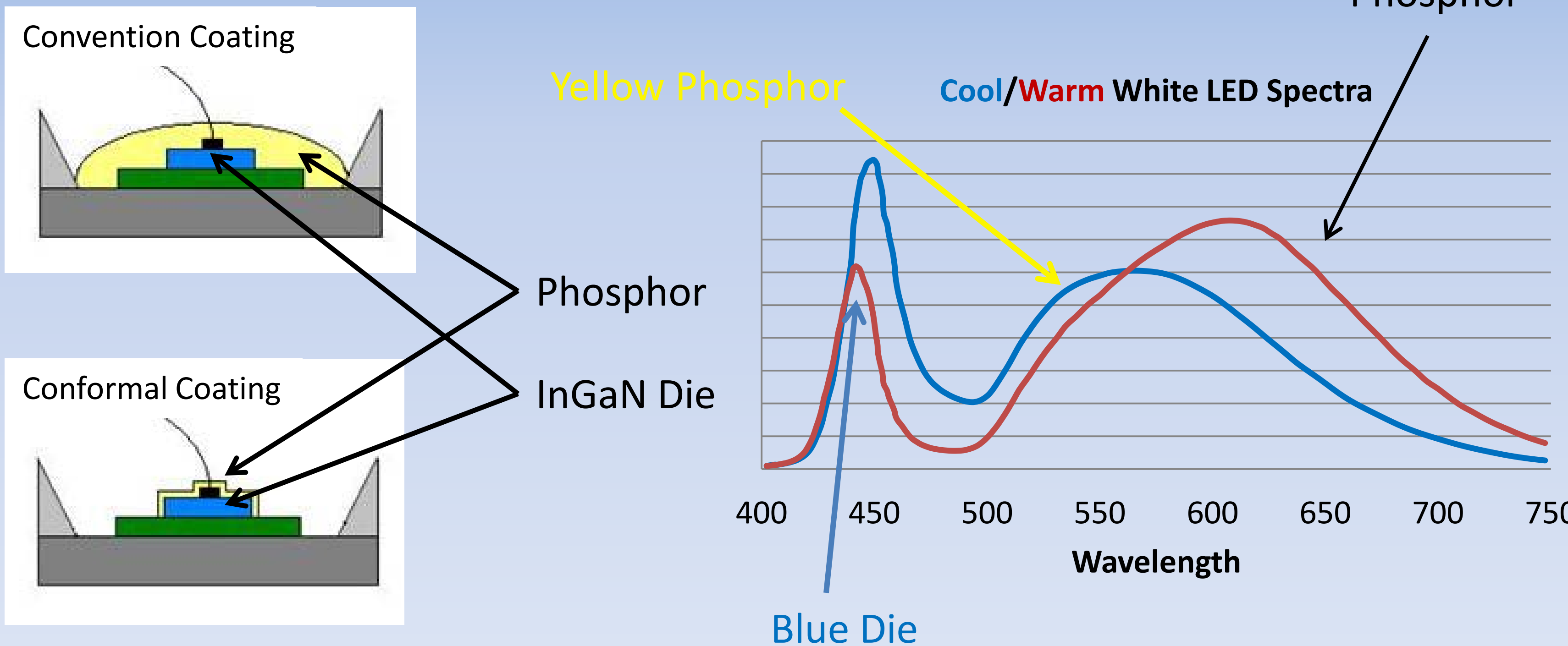


Creates heat instead of light

How Do You Make a White LED?

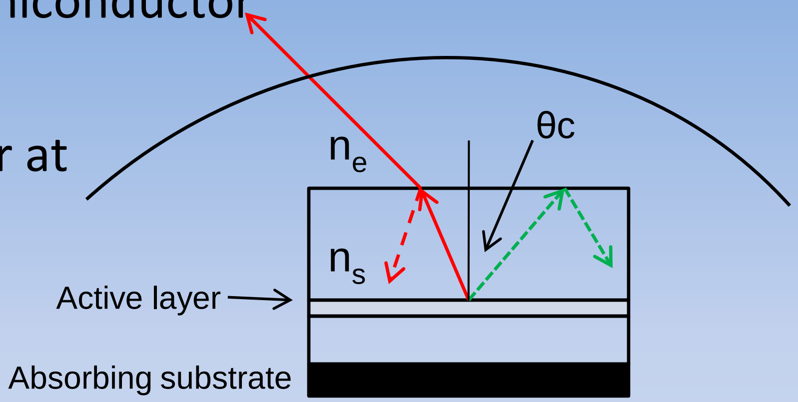
Downconverting Phosphor

- Blue LED + YAG (Yttrium aluminum garnet) = **Cool White**
- Blue LED + YAG + Other phosphor (red, green, etc.) = **Warm White**
- UV LED + Red phosphor + Green phosphor + Blue phosphor

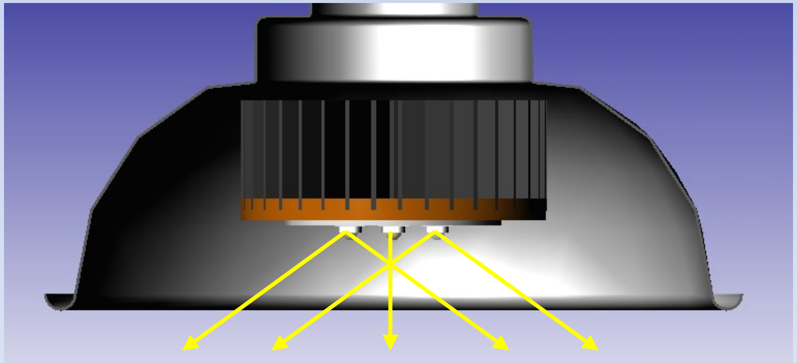


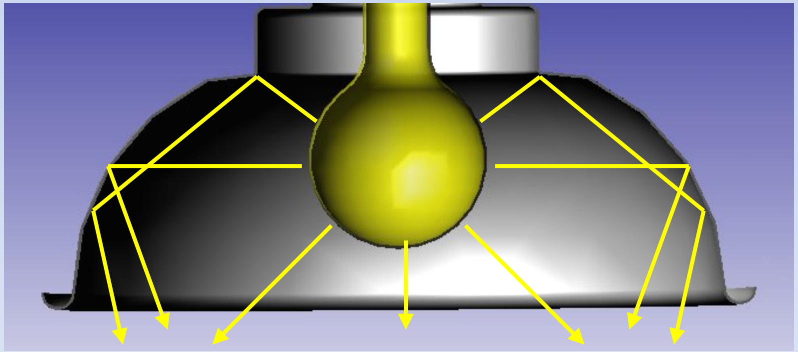
Equivalence – LEDs are Inherently Directional

Due to the high Index of Refraction of the semiconductor (n_s) as compared to the dome material (n_e), by Snell's law, photons exiting the active layer at angles greater than the escape cone angle θ_c will be reflected back into the semiconductor and will not exit the device.



This gives rise to LED's high directionality and often better efficacy in certain luminaires





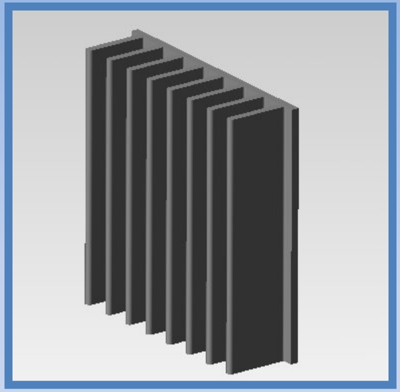
But be cautious – Equivalence can be a slippery slope!

Thermal Choices – How to orient the luminaire

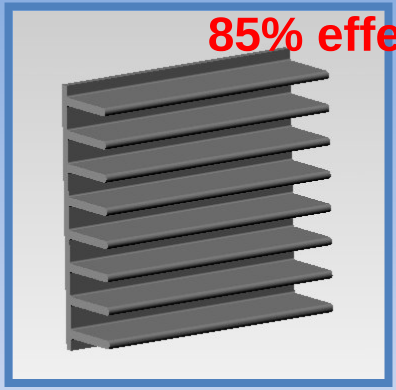
Luminaire manufacturers must take desired orientations into account when designing thermal management system for products

LM-79 testing standard requires the luminaire be tested in the orientation in which it will be mounted

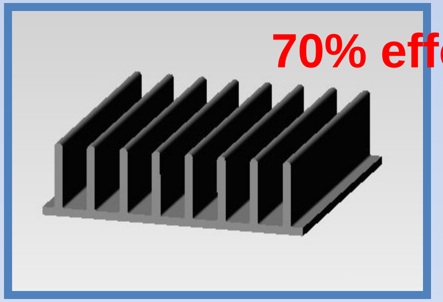
100% effective

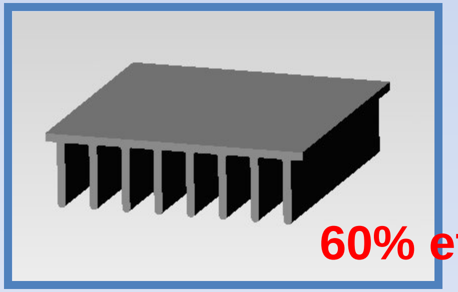


85% effective



70% effective





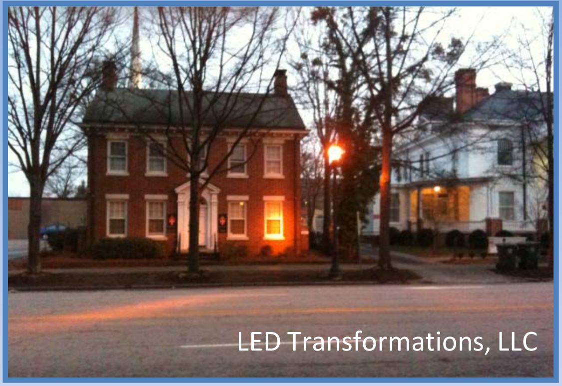
60% effective

Differences

Optical Choices – Be careful what you ask for, you might get it

- Is the environment over lit?
  - How much is spec and how much habit?
- How important is uniformity?
- What effect does CCT have on perception of brightness?
- Will users accept the sharp cut-off that LED sources can provide (e.g. street lights, sidewalks; lampshades)?
- Be cautious of light emitted between 80° and 90° – Contributes to disability and discomfort glare

Cut-off Extremes



Differences

Semi-Conductor Heritage – Rapid changes are expected

The traditional lighting industry moves at a relatively slow pace with styles changing regularly, but technology remaining relatively constant

The semi-conductor industry moves at a rapid rate with components changing constantly. It is the epitome of the "disposable" society

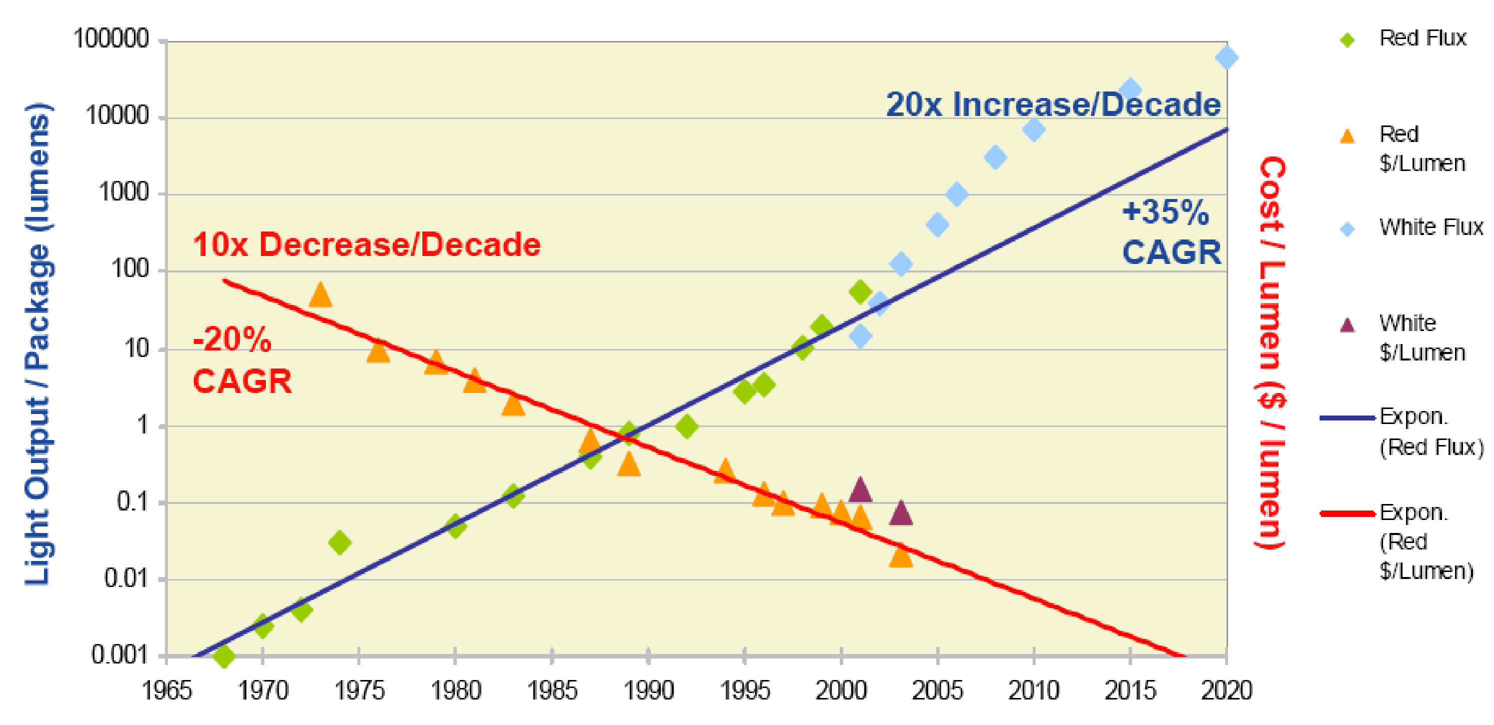
(1971) 4 bit 8 bit 16 bit 32 bit 64 bit (1991)

In the Solid-State Lighting world, these two cultures clash head-on with major implications for both

Differences

Semi-Conductor Heritage – Rapid changes are expected

LEDs follow a development rule known as Haitz's Law



Source: Roland Haitz & Lumileds

Differences

Semi-Conductor Heritage – Rapid changes are expected

LED Metrics Roadmap

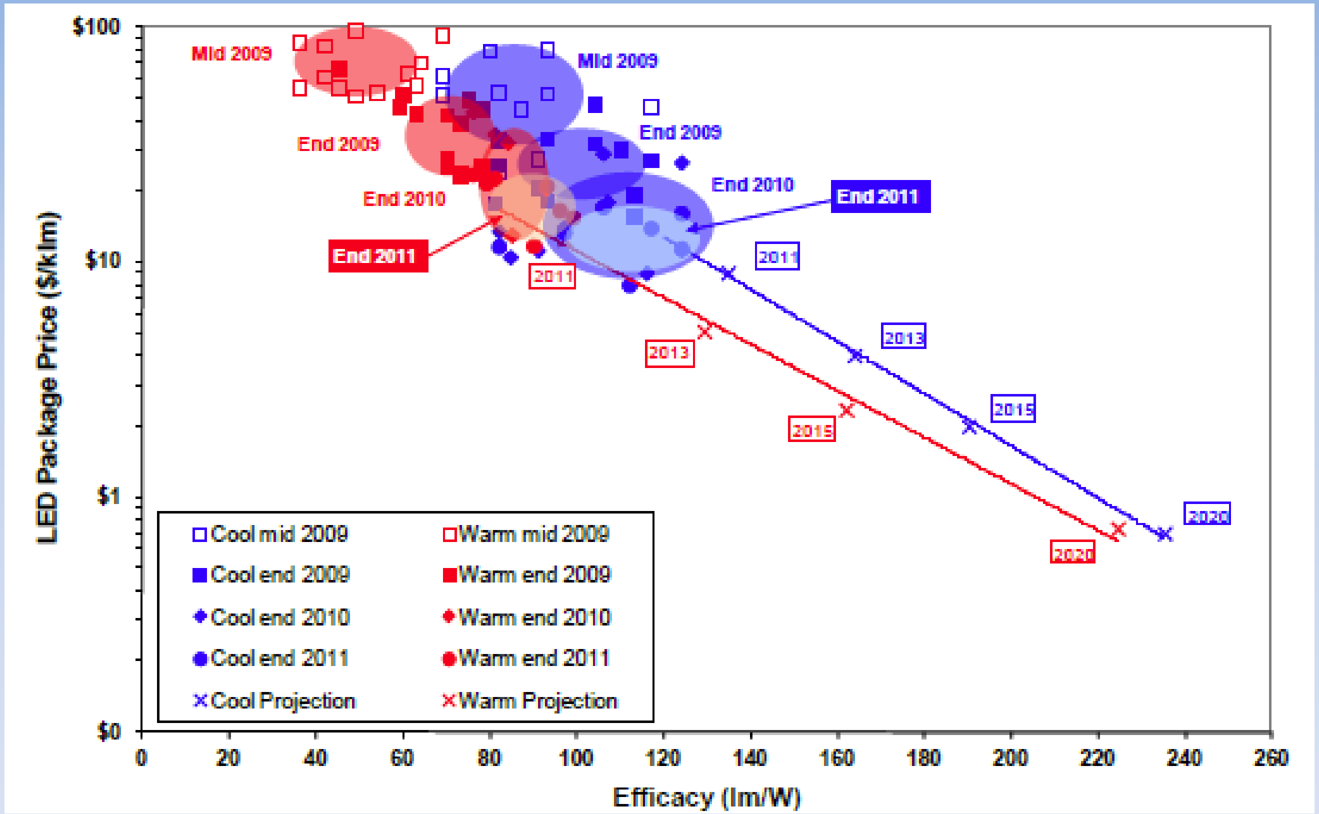
Metric	Unit	2011	2013	2015	2020	Goal
LED Efficacy (warm white)	lm/W	98	129	162	224	266
LED Price (warm white)	$/klm	12.5	5.1	2.3	0.7	0.5
LED Efficacy (cool white)	lm/W	135	164	190	235	266
LED Price (cool white)	$/klm	9	4	2	0.7	0.5

Source: 2012 DOE SSL Multi-Year Program Plan

Differences

Semi-Conductor Heritage – Rapid changes are expected

LED Metrics Roadmap

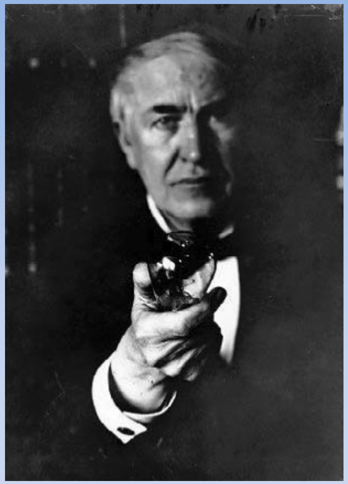


Source: 2012 DOE SSL Multi-Year Program Plan

Differences

Obsolescence – Part of the semi-conductor world

- If Edison were alive today, he would certainly recognize his light bulb



- If you owned this fixture, you could still get lamps for it

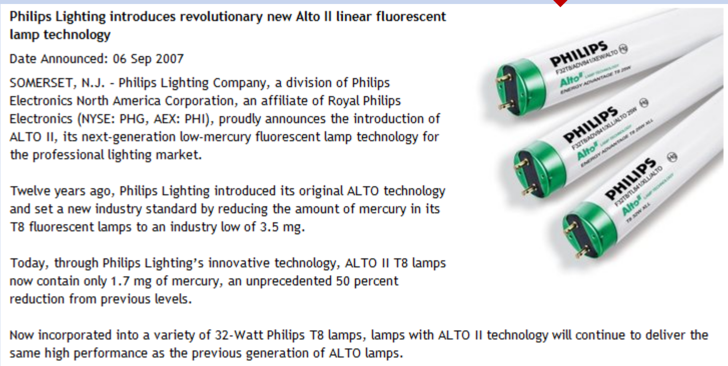
Source: Scot Hinson, Modeliving

Differences

Obsolescence – Some things don't change

A 1942 Magazine ad for General Electric fluorescent lamps

A 2007 news release from a lighting magazine on an improved fluorescent lamp



Philips Lighting introduces revolutionary new Alto II linear fluorescent lamp technology

Date Announced: 06 Sep 2007

SOMERSET, N.J. - Philips Lighting Company, a division of Philips Electronics North America Corporation, an affiliate of Royal Philips Electronics (NYSE: PHG, AEX: PHI), proudly announces the introduction of ALTO II, its next-generation low-mercury fluorescent lamp technology for the professional lighting market.

Twelve years ago, Philips Lighting introduced its original ALTO technology and set a new industry standard by reducing the amount of mercury in its T8 fluorescent lamps to an industry low of 3.5 mg.

Today, through Philips Lighting's innovative technology, ALTO II T8 lamps now contain only 1.7 mg of mercury, an unprecedented 50 percent reduction from previous levels.

Now incorporated into a variety of 32-Watt Philips T8 lamps, lamps with ALTO II technology will continue to deliver the same high performance as the previous generation of ALTO lamps.

"General Electric MAZDA fluorescent lamps are Made to Stay Brighter Longer!"

"*What makes you so sure?*"

"They're checked and double-checked all the time. G-E MAZDA F lamps are subjected to hundreds of tests and inspections covering all important defects."

"*By whom?*"

"By a nationally known independent electrical testing laboratory as well as by experienced G-E inspectors."

"*How many lamps are tested? Two or three thousand?*"

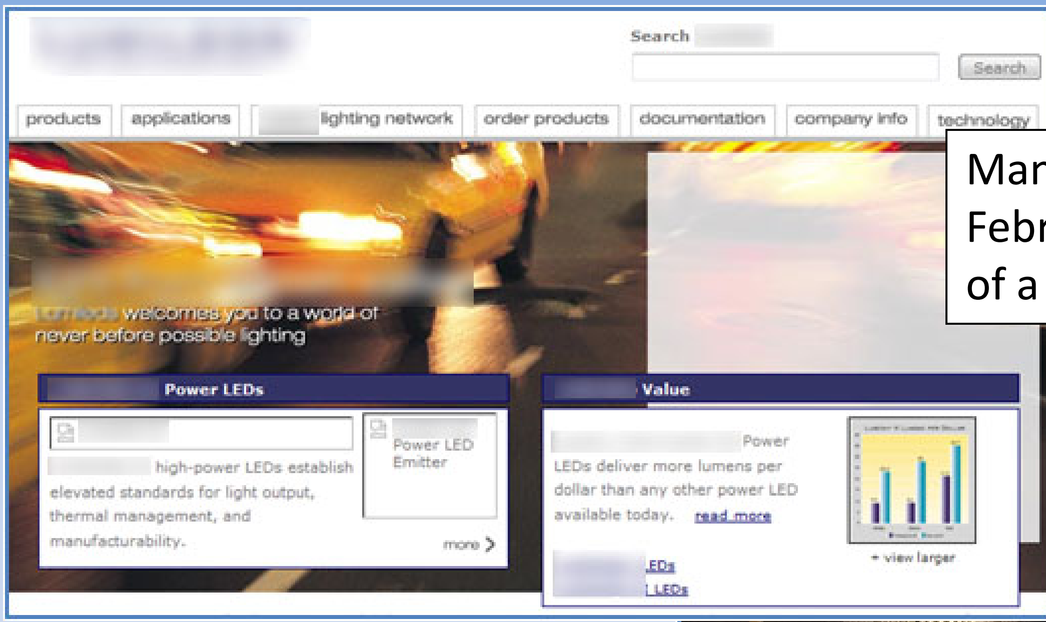
"Nearly one million lamps every year . . . and remember, these tests are in addition to those made by G-E in its own factories."

G-E MAZDA LAMPS

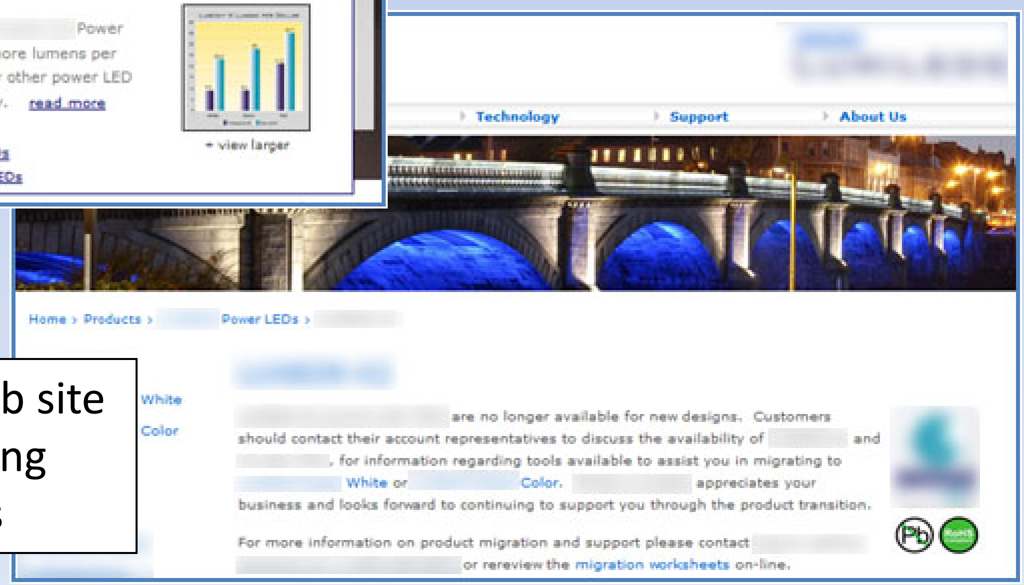
GENERAL ELECTRIC

Differences

Obsolescence – And some things do



Manufacturer's web site from February 2006 showing the addition of a new line of LED devices



The same manufacturer's web site from March 2010 discontinuing that same line of LED devices

Differences

Obsolescence – Its effect on availability of product

It doesn’t save energy if you can’t get it

- Lighting is typically ordered late in the construction process. Backorder status because vendor builds in batches or ships quarterly from overseas does not help.
- Importance of spares when things do break or fail
  - As more LED-based products become available, this should be less of an issue
- Availability 5 years from now

Quantity	Catalog Number	Description	Ship Status	Unit Price	Total
5	DL - 2700-6-120	LED Downlight (2700K), 6" 120VAC	BACKORDERED	$119.95	$599.75
15	DL - 3000-8-120	LED Downlight (3000K), 8" 120VAC	BACKORDERED	$139.95	$2,099.25
50	CL - 3000-1-24	LED Cove Light (3000K), 1', 24VDC	BACKORDERED	$45.00	$2,250.00
10	WW - 3500-5-120	Wall Wash (3500K), 120VAC	BACKORDERED	$279.00	$2,790.00
15	DL - 3000-6-120	LED Downlight (3000K), 8" 120VAC	BACKORDERED	$139.00	$2,085.00
					$0.00
					$0.00
Total for this order					$9,824.00

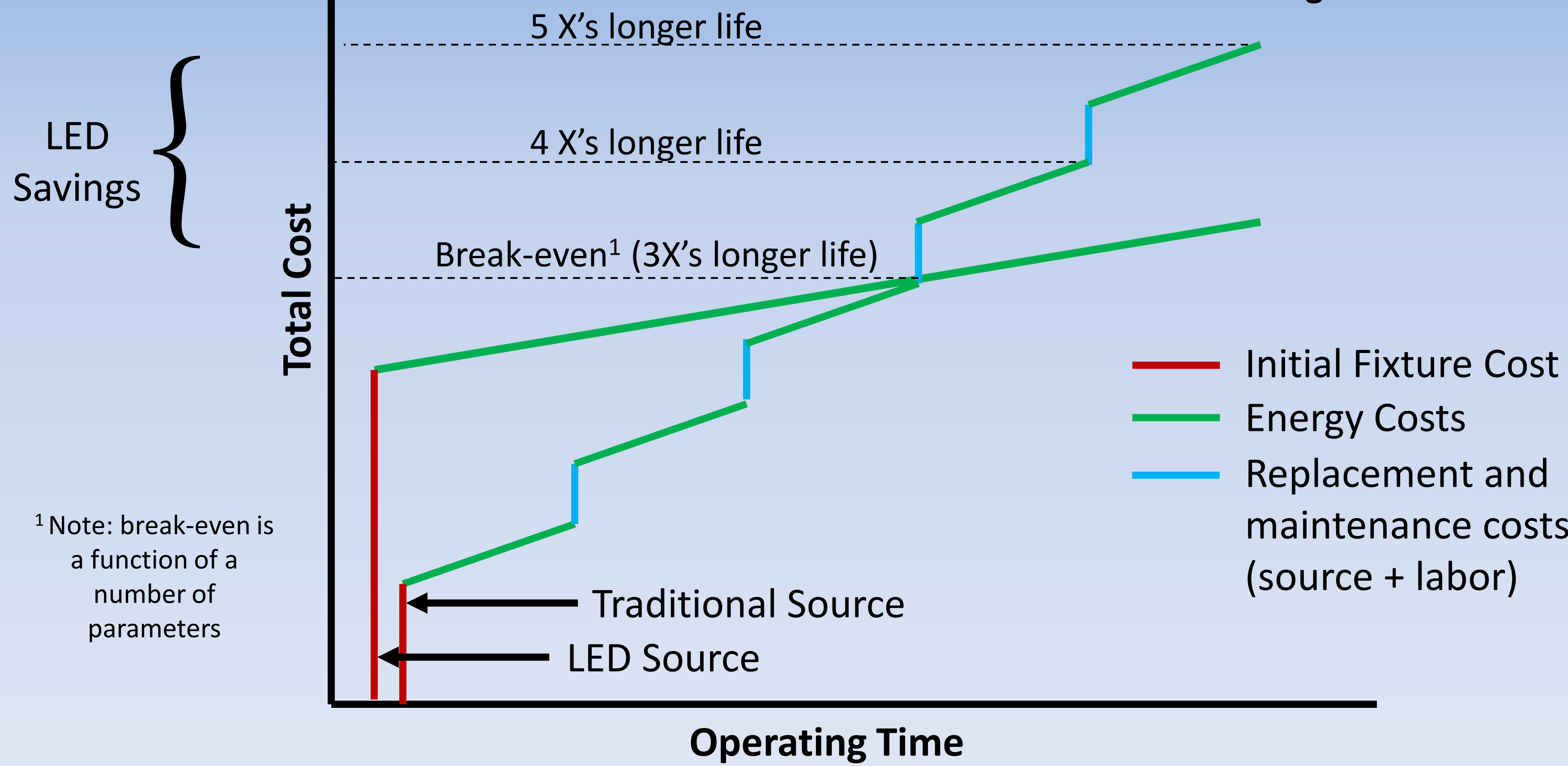
LED Lifetimes

- Traditional light sources fail catastrophically due to electrodes which weaken or become contaminated and eventually fail, causing the lamp to stop working
- LEDs rarely fail catastrophically
  - Light output gradually decreases over operating time
  - End of life defined to be when light output reaches 70% of initial value
    - Raises issue for designers – how to warn users that product has exceeded end-of-life and is producing less light than the application may require
  - Lifetime highly dependent on temperature (ambient and device as well as operating current

Why do We Care? – Longer life = greater payback

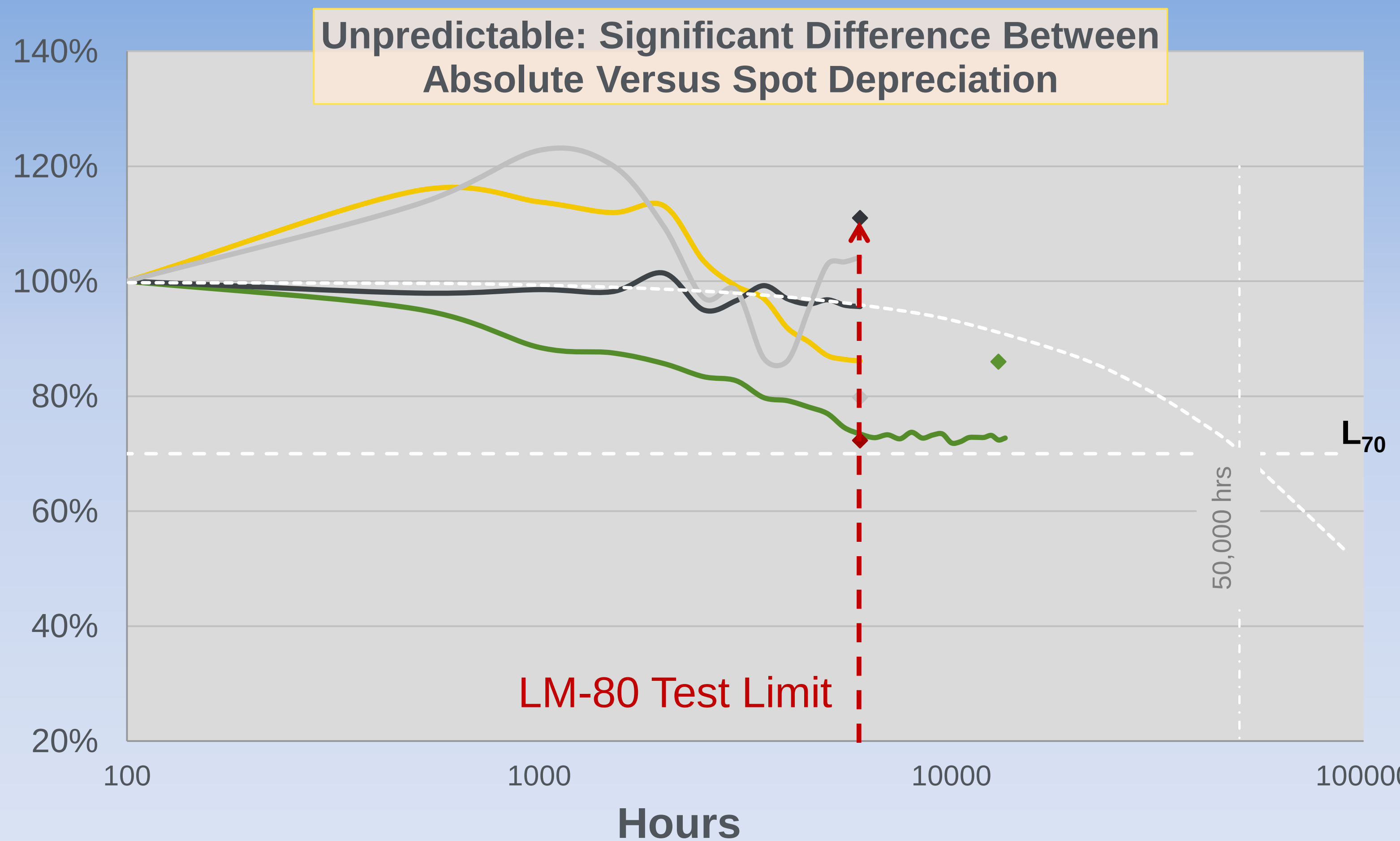
Where are the savings for LED lighting?

The longer the life difference, the greater the savings for the LED light source



[1] Note: break-even is a function of a number of parameters

LED Lifetimes – A measurement issue



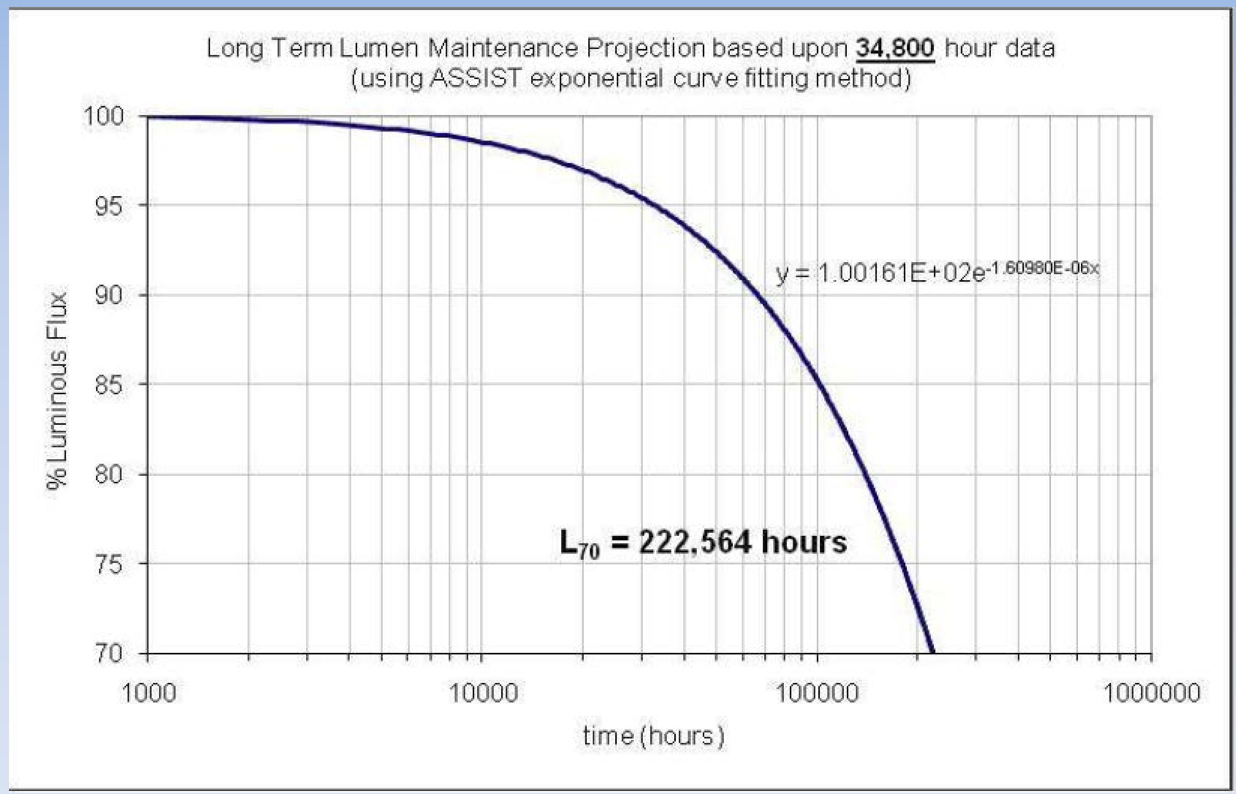
CALiPER Round 10 data, www.ssl.energy.gov/caliper.html

LED Lifetimes – A measurement issue

It is difficult to predict the long term performance of a device with only early lifetime data

34,800 Hours of data

Almost 3.5 X's longer predicted lifetime than the 6,000 hour results

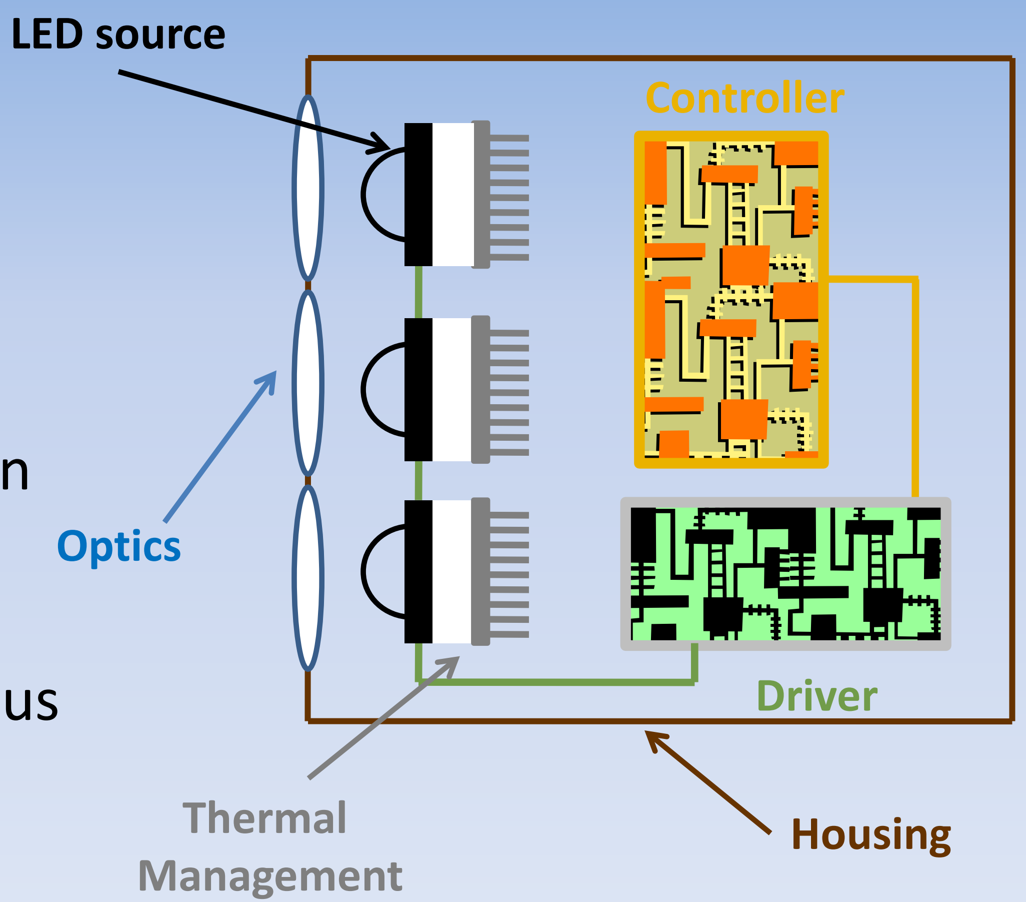


Source: Cree

Critical to Remember – A Luminaire is a System

The failure of any one component can cause the entire system to stop functioning

Luminaire designers make trade-offs among the components, depending on the desired performance criteria – for example the number of LEDs ($$$) versus drive current (lifetime)



Lifetime

Component & Fabrication Choices – Effect on Reliability

Two examples of failures caused by the driver

Stop & Shop, Raritan, NJ – 6 weeks

City Center, Las Vegas – 5 months

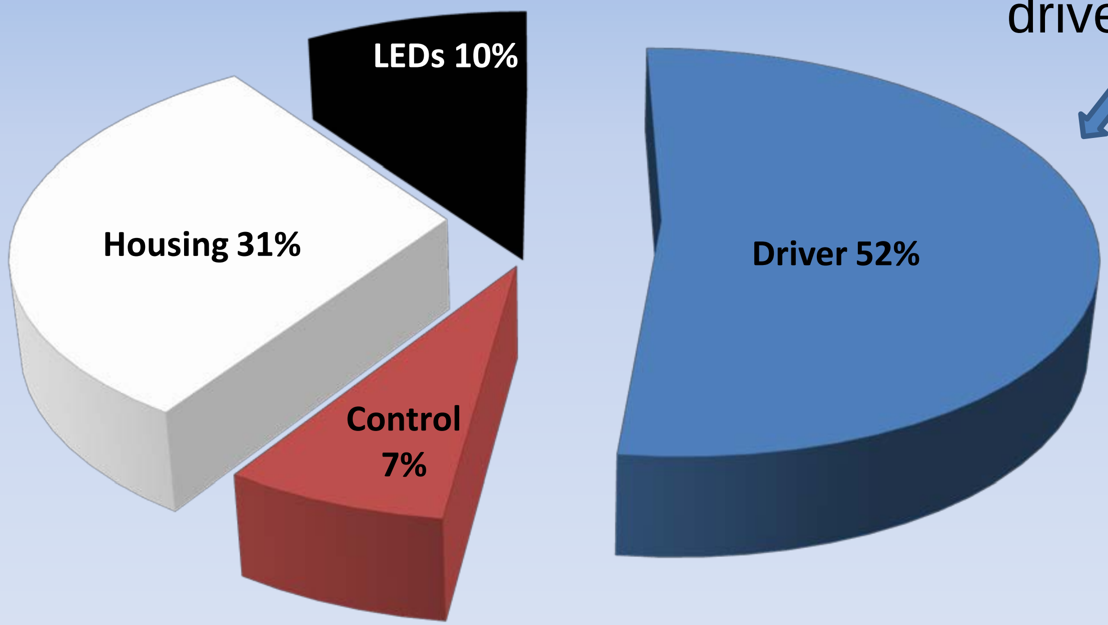
Not quite 50,000 hours!

Component & Fabrication Choices – Effect on Reliability

In one study it was found that 90% of the luminaire failures were due to something other than the LEDs!

Failure Distribution

Over half were driver failures



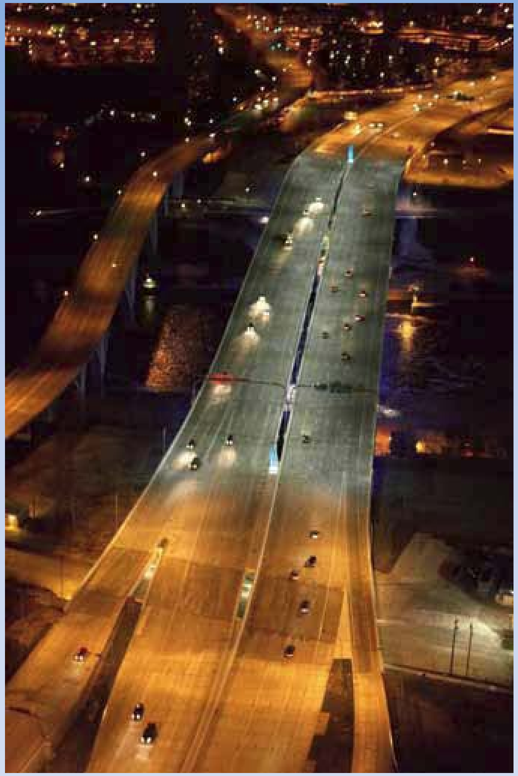
Total number of failures = 29 out of 5,400 units installed (0.54%)

Source: Appalachian Lighting Systems

Pilot Programs – Little problems don't become major disasters

I35 Bridge project in Minneapolis found lumen depreciation in 20 units used on the bridge which far exceeded manufacturer's predicted results:

Reason #1: "Earlier design used an optical gel to fill void between LED lens and proprietary *nano-optic*. Over time, a bubble forms in the gel that causes step change in both lumen distribution and output. The measured optical gel impact on these two samples corresponds to 6.6% and 7.4% reductions in total lumen output."



Reason #2: Dirt Depreciation

Site	Years of Operation	Lumen Output (Dirty Lens)	Lumen Output (Clean Lens)	Lumen Dirt Depreciation
I-35W	1.25	14520	15227	4.60%
I-35W	1.25	14670	15245	3.80%

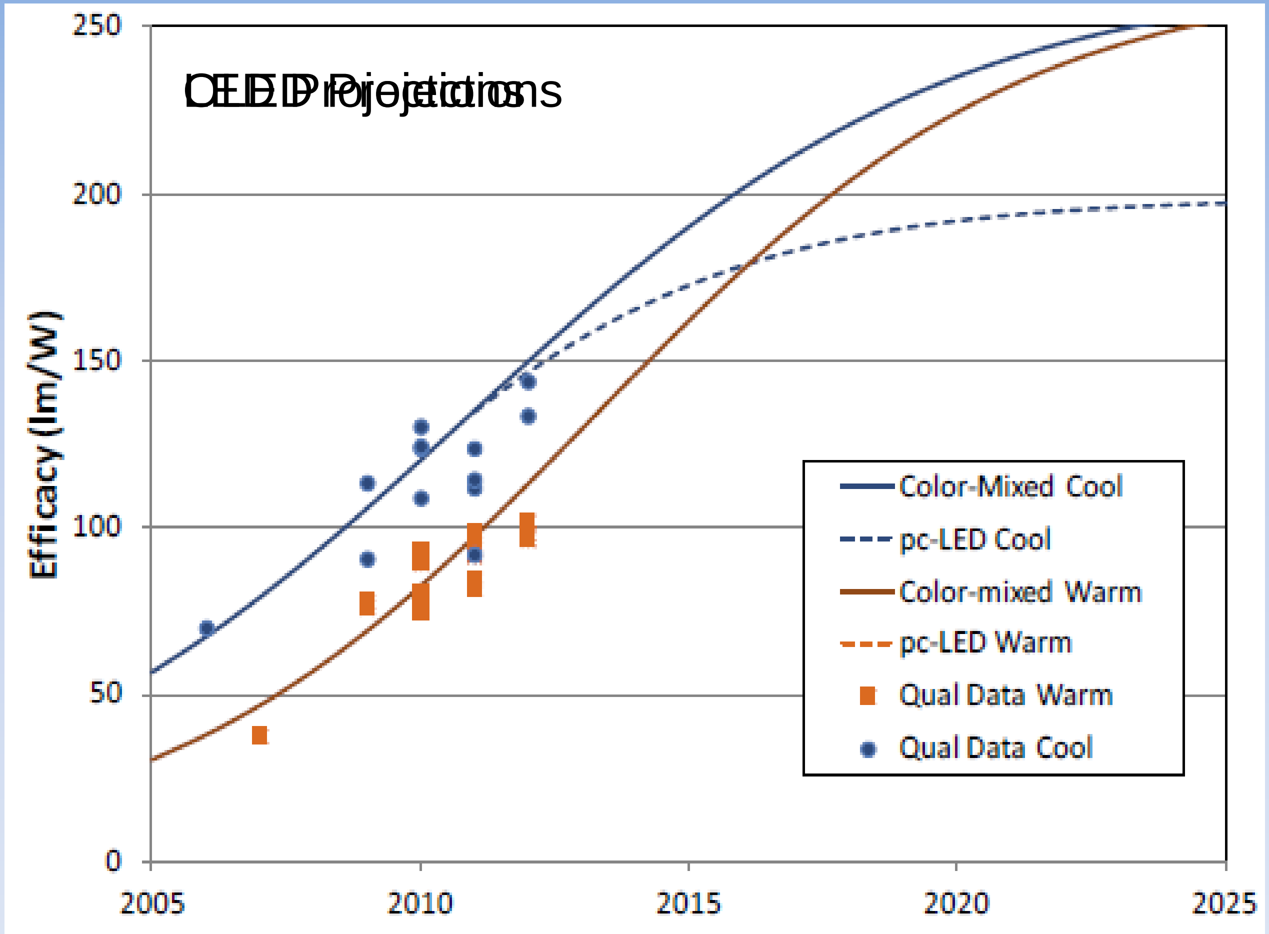
Would translate to a 9 year lifetime due to dirt depreciation alone!

OLEDs

Efficacy – Comparison of LED vs. OLED devices

Comparison of OLED and LED Target Projections

SSL Multi-Year Program Plan, April 2012



Efficacy – Comparison of LED vs. OLED devices

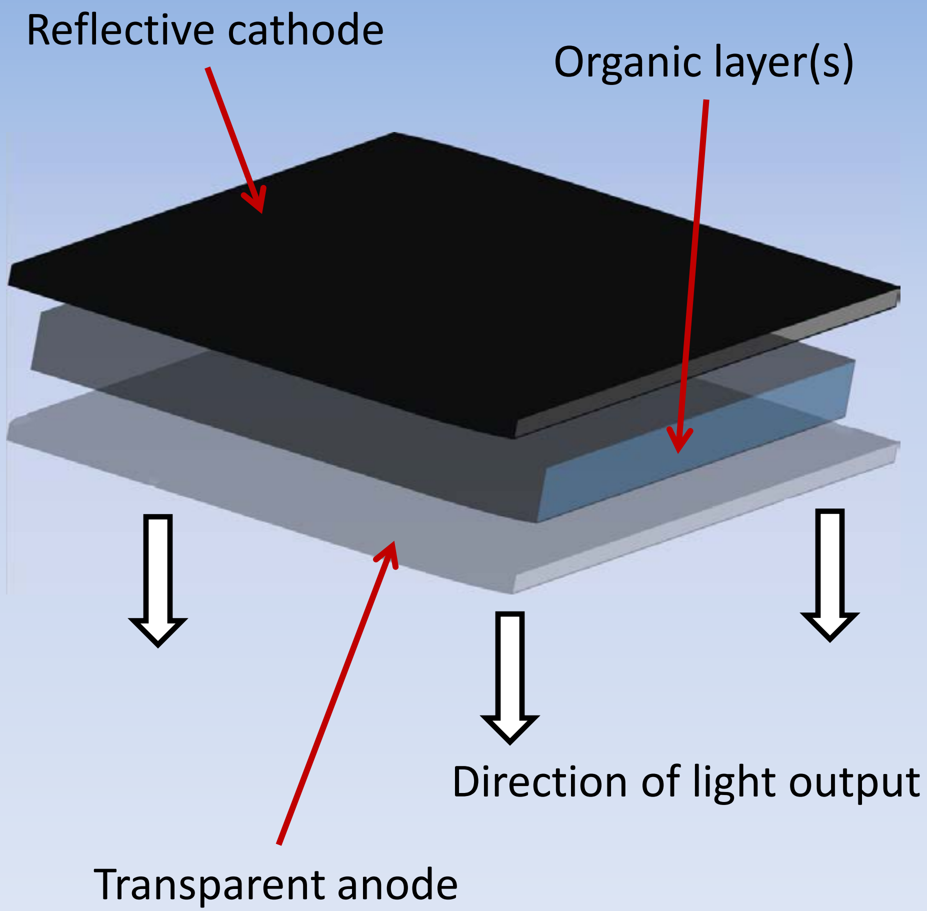
Metric	2011	2013	2015	2020	Goal
Cool White[1] Efficacy (lm/W)	135	164	190	235	266
Cool White[2] Efficacy (lm/W)	135	157	173	192	199
Warm White[1] Efficacy (lm/W)	97	129	162	224	266
Warm White[2] Efficacy (lm/W)	98	126	150	185	199
OLED Panel Efficacy (lm/W)	58	80	100	140	190

[1] Color-mixed [2] Phosphor

Source: GE

What is an OLED?

- An OLED or organic light-emitting diode is a semiconductor device which consists of an electroluminescent organic layer(s) sandwiched between two electrodes, one of which is transparent.
- The device is fabricated by sequentially depositing organic layers on a conducting substrate followed by another conducting electrode.
- A common device structure comprises a glass substrate coated with indium tin oxide (ITO) as transparent anode and a thin, opaque metal film as cathode.
- Typical separation between layers is 100 nm or less



A Close-up View of an OLED

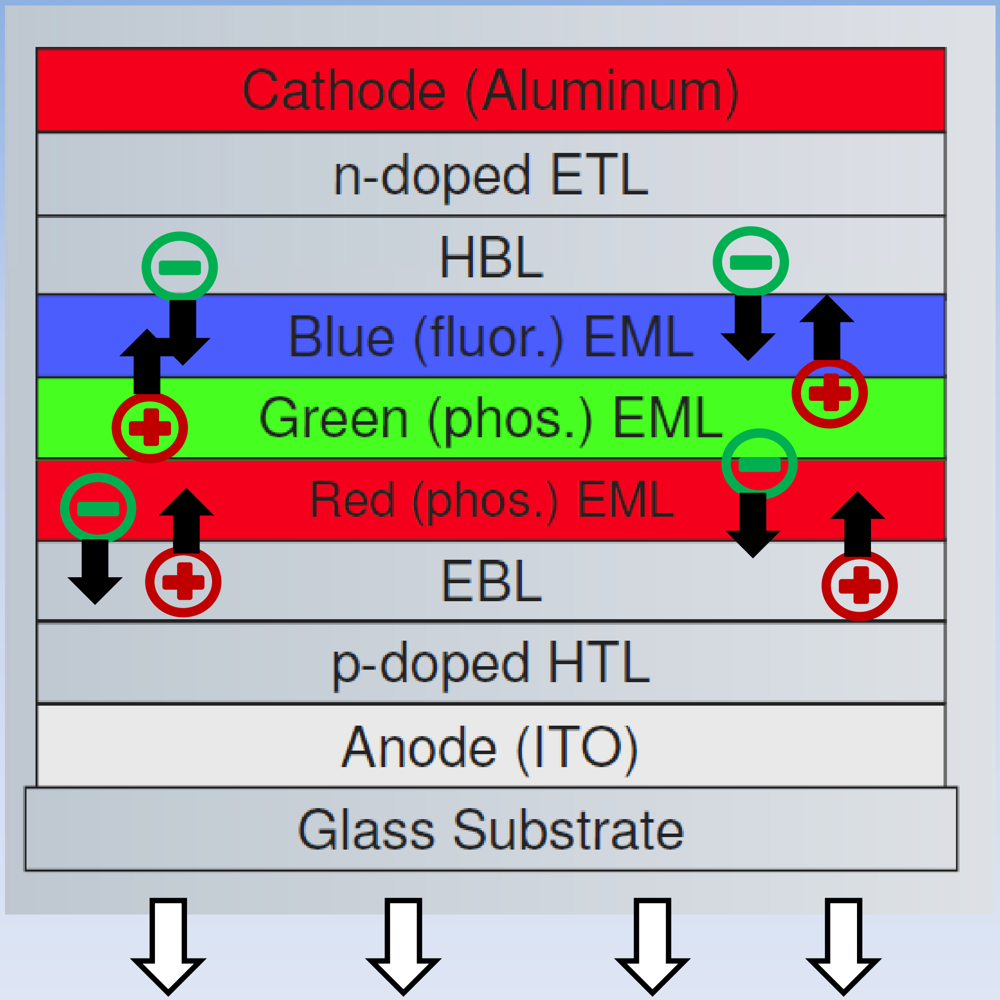
Electron **T**ransport **L**ayer

Hole **B**locking **L**ayer

Emission **L**ayers

Electron **B**locking **L**ayer

Hole **T**ransport **L**ayer



Some OLED Terms

- Small molecule OLEDs – (SM-OLEDs)
  - Majority of today's devices, high performance, generally deposited by vapor phase deposition
- Large molecule OLEDs – (P-OLEDs or Polymer OLEDs)
  - Are solution processable (i.e. ink-jet printing and spin coating fabrication)
- Fluorescent materials (less efficient but last longer)
- Phosphorescent materials (more efficient/lower lifetime blue)
- Gen – typically more applicable to display technology
  - Refers to the generation of glass panel manufacturing line. Each generation is capable of producing larger and larger panels of glass. This brings down the cost of the substrate on which the OLED is manufactured.

OLEDs

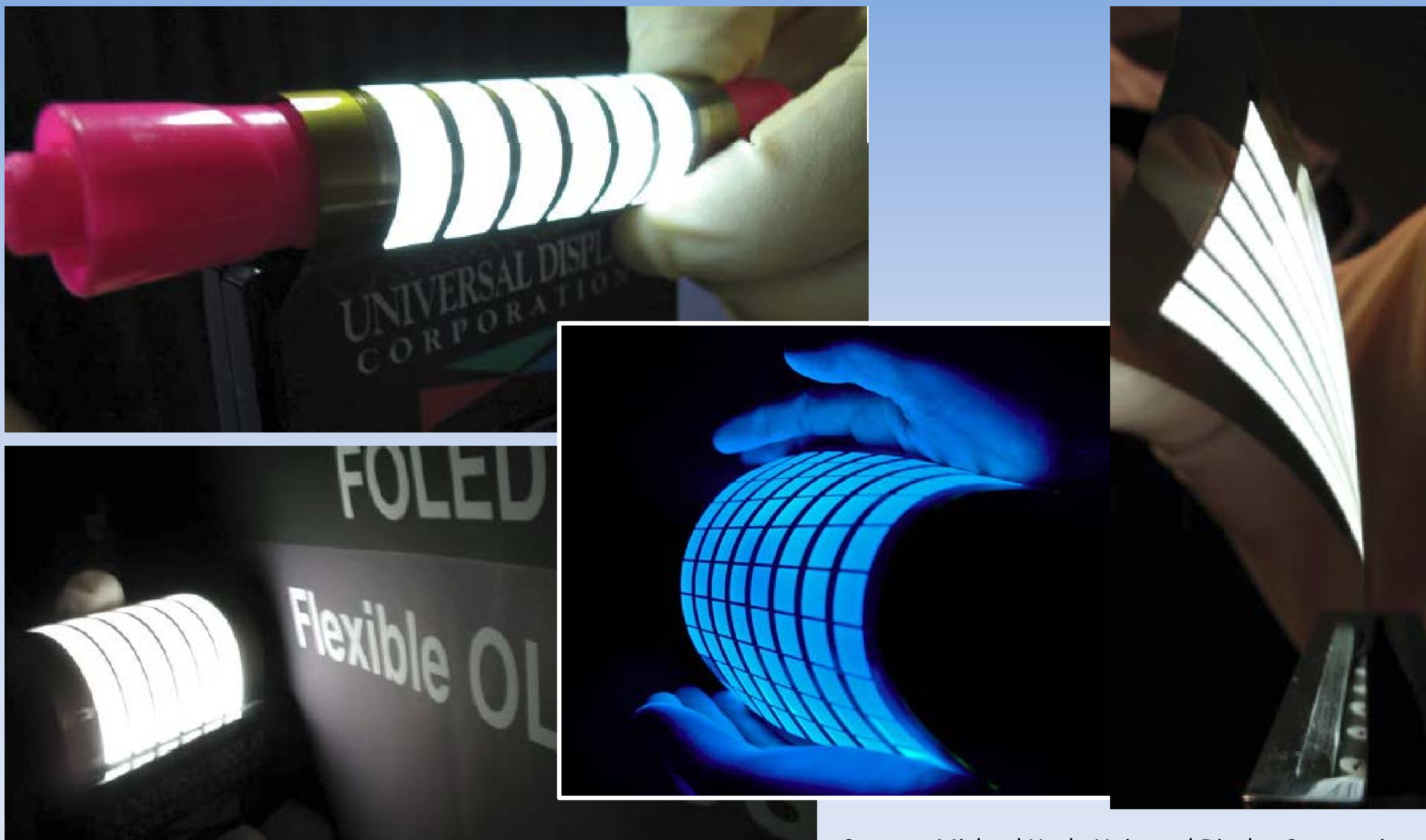
Unique Features

- Flat Form Factor
  - Emits light over entire surface; also allows for easy heat dissipation
- Flexibility
  - As encapsulation techniques improve, ability to use flexible substrates such as metal foils or plastic
- Color Tunability
  - Spectra depends on the emitter material; generally wider and more flat than that of inorganic LEDs
- Efficiency
  - Target for 2020 is 190 lumens/W
  - Very low luminaire efficiency losses
- Transparency
  - Transparent OLEDs can be made which emit light from both sides when on, and are see-through in their off state (using transparent electrodes & substrate materials)

Source: DuPont Displays

Source: Novaled

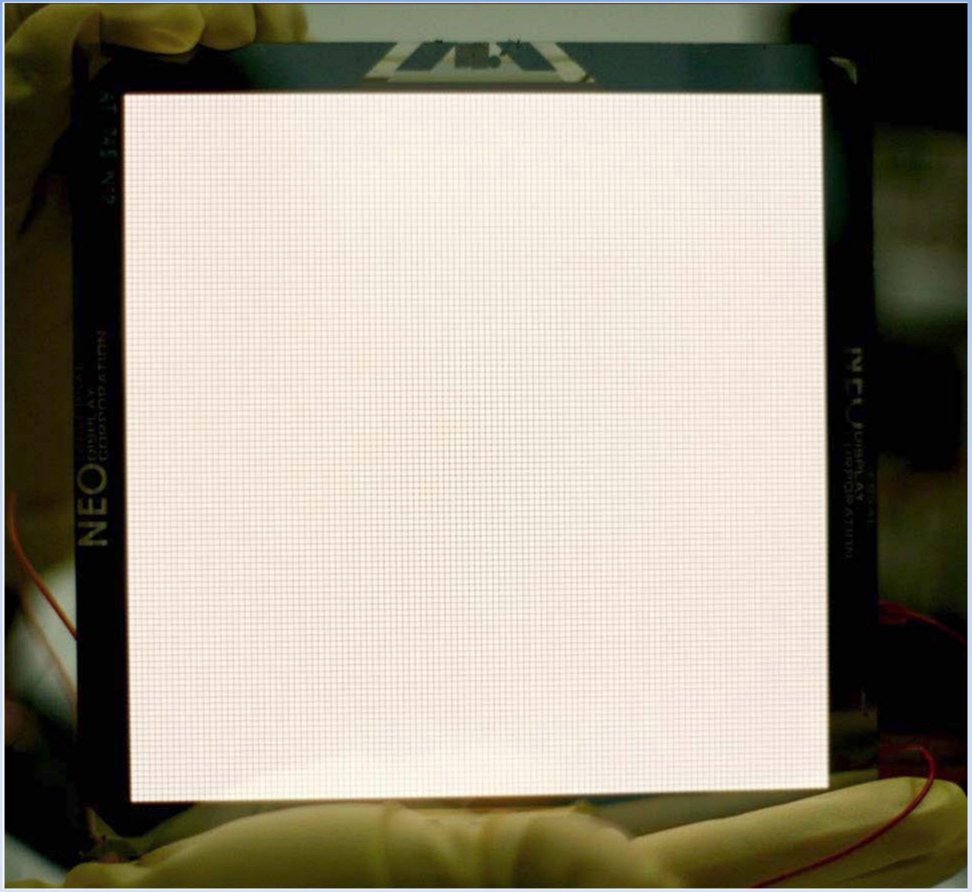
Unique Features – Flexibility



Source: Michael Hack, Universal Display Corporation

Unique Features – Uniform lighting surface with minimum glare

Dimension	15 cm x 15 cm
Active Area	134. 6 cm^2
Fill Factor	77%
Luminance [cd/m^2]	3,000
Luminance Uniformity	88%

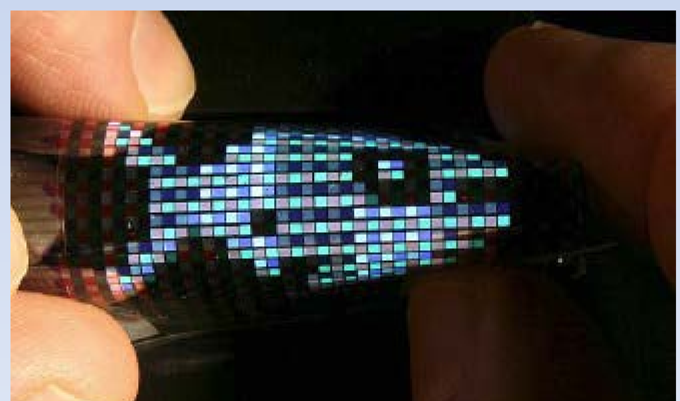


Source: Universal Display Corporation

OLEDs

Unique Features – Transparency (disappears when not in use)

Source: Universal Display Corporation

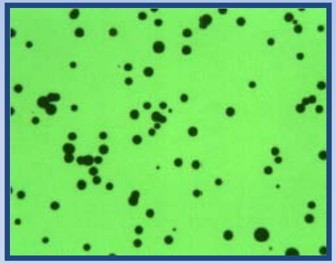


Source: Yuan-Sheng Tyan, Kodak

The Major Issues

Issue	Problem	Solution
Efficacy	Some lab devices can compete with conventional technologies, early products have low efficacy	Work needed to develop efficient, long-lasting blue emitter; next generation products reaching levels that compete with conventional lighting sources
Lifetime	Short lifetimes for blue materials; susceptibility to moisture intrusion	Work needed on high current density, more stable materials, better and low cost encapsulation
Light Output	Current OLED packages produce “dim” light	Work needed to improve light extraction, high current density
Cost	Too high; lower cost device and luminaire materials are needed	Infrastructure investment needed to develop commercial OLED products
Testing Standards	No standards presently available for testing OLED products	Need for reliable test methods standards to establish consistency and reduce uncertainty

OLED defects caused by moisture



Source: Yuan-Sheng Tyan Kodak

OLED Applications

Niche Products – New form factors but high cost

Source: Osram

Source: Blackbody (Astrom FIAMM)

Photo Credit: ©John Sutton Photography 2011

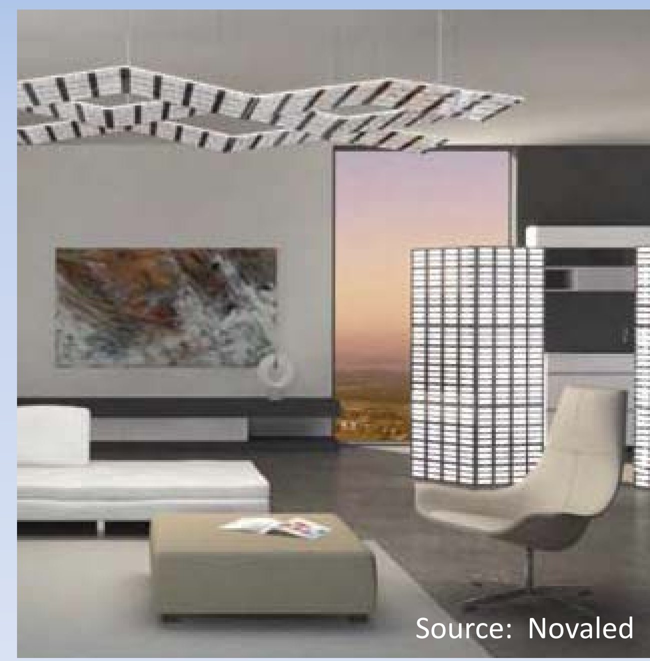
Source: Philips Lumiblade

Source: Universal Display Corporation

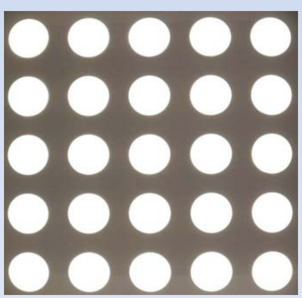
OLED Applications

Niche Products – New form factors but high cost

- Offers Architects/Lighting Designers the ability to eliminate the distinction between light source and luminaire
- Its creates a plane of light with no perceptible volume
- Its form factor is very flexible allowing widely varying form factors and shapes
  - Future flexible substrates will allow infinite variation in shapes
- Provides soft, glare-free illumination without requiring diffusers, baffles, etc.



Source: Novaled



Source: Acuity

Final Thoughts

A Simple Suggestion

Do not underestimate the use and practical application of simple COMMON SENSE

- If it seems too good to be true, it probably is
- If you can't understand how a product could do "that," there is a high likelihood that it probably "doesn't"
- If nobody else's product does "that" maybe this product does not do it either

Which lamp would perform better?

Final Thoughts

A Lesson from History

- Think of how the microprocessor has changed the world over the last 30 years.

- The lighting world is about to undergo a change not seen since the invention of the incandescent lamp, and driven by that same semi-conductor industry.

Are you going to be ready for it?

Thank You

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